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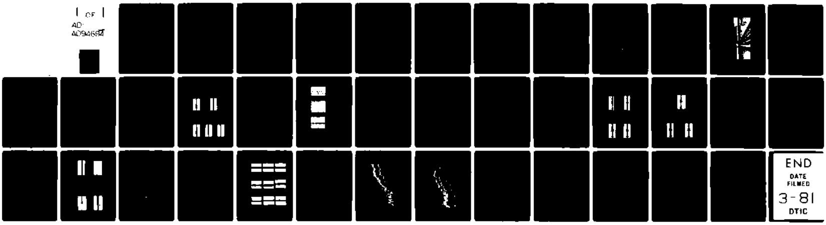

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FEASIBILITY STUDY OF AIRBORNE BATHYMETRIC SENSING USING THE CO_2 LASER/ACOUSTIC TECHNIQUE (BRIGHTON DAM TEST RESULTS)

G. Daniel Hickman
Applied Science Technology, Inc.

and

B. S. Maccabee
C. E. Bell
Naval Surface Weapons Center

Technical Report Prepared Under Contract N00014-78-C-0764

for

The Office of Naval Research
Coastal Sciences, Code 462
Arlington, Virginia 22217

and

The National Ocean Survey
Engineering Development Laboratory
Riverdale, Maryland 20840

May 1980

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ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. James S. Bailey, Office of Naval Research (Code 462) for primary contract support and for serving as Program Manager.

Sincere appreciation is also expressed to John Pijanowski and Maurice Ringenbach, Engineering Development Laboratory of the National Ocean Survey for technical guidance and partial contractual support.

ABSTRACT

A feasibility experiment was performed on a concept for a remote system for bathymetric mapping in turbid shallow waters. The concept consists of a CO_2 laser transmitter and a microphone receiver. The CO_2 laser is used from a platform in the air to generate an acoustic field in the water, while the microphone (in air) detects the sound pulses, after being reflected off the bottom sediment. The results of these experiments definitively proved that the CO_2 laser/acoustic technique could be used to derive bathymetric data using a microphone located in the air. The possibility therefore exists that this technique could be used as the basis for a remote sensing system for shallow water bathymetry. Similar type measurements were also made of acoustic reflections from an aluminum plate located at various water depths. Calculations of the Sound Pressure Levels (SPL) are in good agreement with SPL's measured with a hydrophone in the water. However, large discrepancies exist between measured and calculated SPL's with the air-located microphone. The resolution of these discrepancies, which are thought to be due to a malfunction of the microphone, will be one of the objectives of future experiments.

I. INTRODUCTION

Rapid surveillance of inshore waters has drawn the attention during the past several years of both the Navy and Marine Corps as well as civilian agencies such as NOS (The National Ocean Survey). Remote detection and mapping of water depths (bathymetry) has been one of the unsolved problem areas of inshore mapping.

Extensive research has been made using pulsed blue-green lasers (LIDARS) to map shallow water depths from aircraft. The results of this work led to the development of several prototype systems. These systems have proven to be accurate, having high mapping rate capability for shallow waters. However, optical LIDAR systems are severely limited by water turbidity. In a good portion of the coastal zones of the world, turbidity would limit airborne LIDAR mapping to water depths shallower than 30 feet. For instance, typical Chesapeake Bay type waters would probably limit this technique to 10 feet or less.

Boat-mounted side-scan sonar (acoustic) systems for shallow water bathymetric mapping have been developed to a high degree of sophistication. However, these systems have been designed to operate with both the transmitter and receiver located in the water. Therefore, data acquisition rates are limited to those that can be obtained by slow survey boats (6-10 knots).

A technical assessment program was initiated by Hickman in 1975 to determine the feasibility of using an airborne acoustic (transmitter and receiver) system for rapidly mapping bathymetry of high turbid (muddy) shallow waters ($\approx$30 feet). This technique, which could be used in conjunction with the blue-green LIDAR system, would have its greatest value in mapping waters in which the optical LIDAR system could not be used. Estimates have been made that at least 15% (probably greater) of the coastal areas can be classified as muddy.

It is anticipated that such an airborne acoustic system, if proven feasible, would be flown on either surface effect ships or helicopters at speeds up to approximately 100 knots.

The data rate would be at least 10 times larger than that obtained by small boats towing conventional sonar equipment. In addition to the increased data rates available from these platforms, areas could be surveyed, that due to their inexcessibility and possible hazardness to small boats, have not been surveyed.

The acoustic frequencies which are being considered for this application range from 10-100 kHz, which are higher than most conventional sonar frequencies. The main advantages of considering acoustic frequencies in this range are listed:

- Good Depth Resolution - the acoustic wavelengths range from 15 cm to 1.5 cm.
- Small Size Transmitter - the size of the transducer can be made small and still satisfy the requirement that the dimension of the aperature be at least several wavelengths.
- Good Spatial Resolution - beam forming techniques can be used to yield an acoustic beam of 1-2 dedegrees.
- Improved Signal to Noise Ratio - the platform noise spectrum, i.e., helicopter, etc., decreases with increasing frequency. The signal-to-noise ratio therefore should improve as the acoustic frequency that is used in detection system is increased.

One of the main problems which had to be addressed was whether or not an air-operated acoustic transceiver would be capable of delivering sufficient power to penetrate the air/water interface, be reflected from the sediment, penetrate the water/air interface a second time and be detected. The main losses for this type of an acoustic echoing system are:

- Water transmission
- Air/water interface
- Sediment reflectance

- Surface roughness
- Air transmission

The results of this 1975 study* were inconclusive in that it was not possible, on the basis of existing theoretical and experimental data analysed in this report, to definitively state the operational feasibility of an airborne acoustic bathymetric system for shallow water mapping.

II. HYBRID LASER/ACOUSTIC TECHNIQUE FOR SHALLOW WATER BATHYMETRY

Because of the inherent problems which exist in producing high frequency acoustic signals having sufficient power for the application of airborne acoustic bathymetry, a new concept was investigated. This concept is based on a hybrid system which consists of an airborne CO_2 laser transmitter and an airborne acoustic receiver (See Figure 1). Such a system would circumvent problems of generating high frequency high power sound, and the 30 dB loss in the Sound Pressure Level (SPL) that occurs at the air/water interface. Note: one air/water interface signal loss still remains with the hybrid laser/acoustic system.

With the hybrid concept the beam from the CO_2 laser transmitter is focused on the surface of the water. The interaction of the laser beam with the water surface causes an explosion and yields an acoustic pressure wave**. The acoustic wave is transmitted through the water and reflects off the sediment back to the water surface. The acoustic energy, after experiencing a 30 dB loss in passing through the air/water interface, is detected with a microphone located in the air.

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* Hickman, G.D., "A New Concept for a Rapid Surveillance Acoustic Bathymetric System," N00014-71-C-0202, Technical Report prepared by SPARCOM, Inc., May 1975.

** CO_2 Laser Induced Acoustic Pulses - Appendix A.

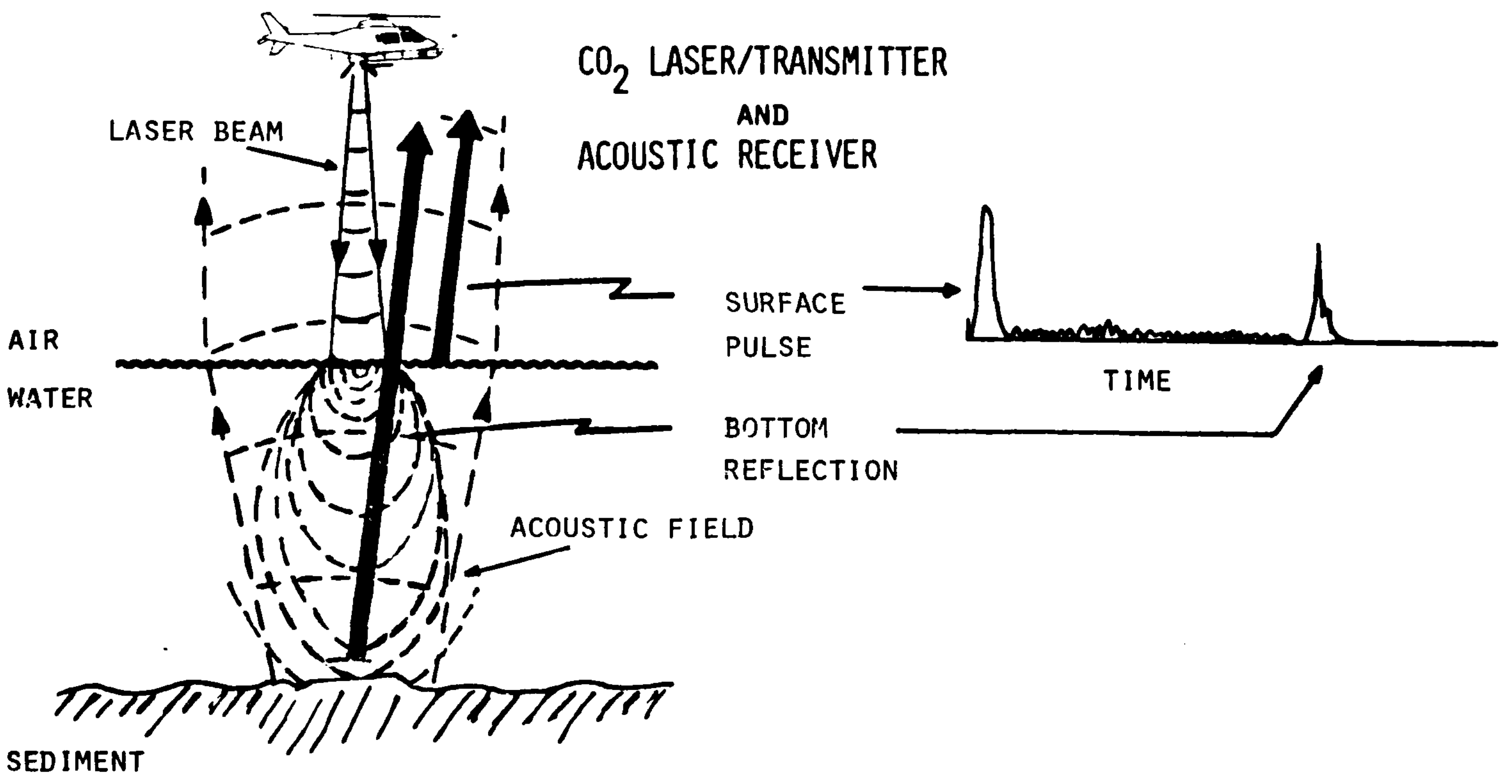


Figure 1 - LASER/ACOUSTIC BATHYMETRY

A. Objective

The principal objective for this program was to determine the feasibility of detecting acoustic energy in the air for the purpose of deriving bathymetric information for shallow water mapping. Measurements of Sound Pressure Levels (SPL) both in the water and air are required for this assessment.

B. Experimental Approach

A series of experiments were designed to test the hybrid laser/acoustic concept for shallow water mapping which could be performed at the Navy's Brighton Dam facility in Maryland (See Figure 2). This facility is a floating laboratory located on a reservoir. The depth of water under the laboratory is approximately 58 feet. A schematic diagram showing the basic layout of the experiments is shown in Figure 3. As shown in this figure, the CO_2 laser is located above the water surface and the beam illuminates a small spot approximately 1 cm in diameter on the surface of the water. A highly sensitive microphone is located above the water to detect the acoustic signal after it is reflected from the bottom sediment. A hydrophone is used in the water to monitor the Sound Pressure Levels of the various reflected signals. A brief description of the transmitters and receivers used in the experiments is given below.

C. Transmitters/Receivers

- CO_2 Laser - (Naval Surface Weapons Center)*
  Type - TEA Laser
  Manufacturer - Lumonics Corporation
  Energy - 5 Joules
  Pulse Rate - 1 pulse/2 sec.
  Pulse Width (Laser) - 3 μsecs.
  Beam Divergence - 4 mrad.
  Flow rate - N_2 - 0.5 l/min.
  He - 0.4 l/min.
  CO_2 - 0.9 l/min.
  Acoustic Pulse Width: 25-50 μsecs.
  Frequency Spectrum 20-40 kHz

* Equipment Owner

Figure 2 - Brighton Dam Facility

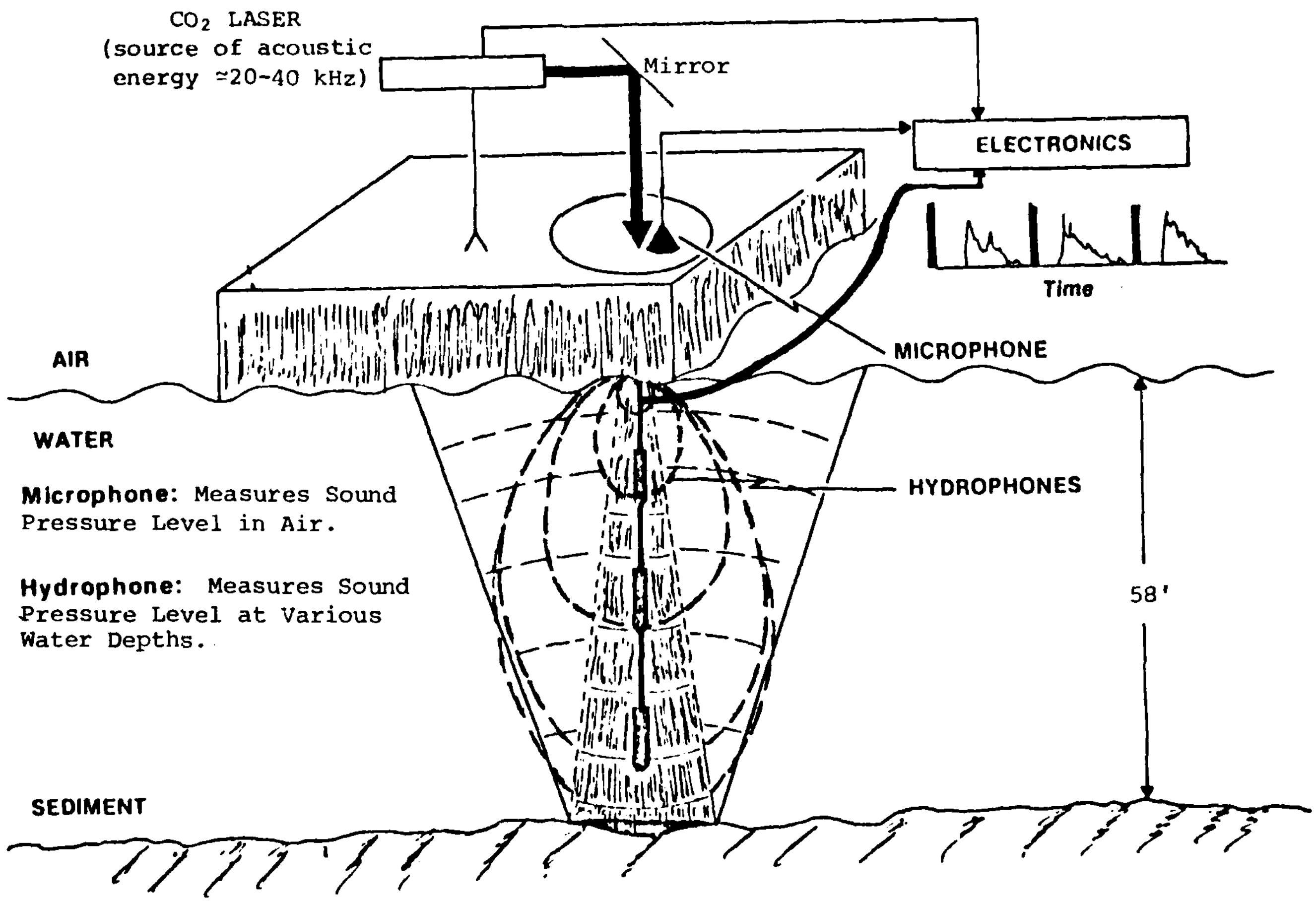


Figure 3 - Brighton Dam Test Program

- Microphone (Applied Science Technology, Inc.)*
  Manufacturer - Bruel & Kjaer
  Type - Condenser Microphone 4149
  Rated Sensitivity: -38.8 dB re 1V/Pa**
  Frequency range - flat to 40 kHz
  Preamplifier - 2619
  Power supply - 2807
  Size - 1/2" diameter

- H-52 Acoustic Receiver - (Brighton Dam Facility)*
  Sensitivity: -187 dB re 1V/μPa
  Size - Active Area: diameter, 0.3 cm
  length, 5.1 cm
  Overall: diameter, 1.0 inch
  length, 6.0 inches
  Frequency Response - flat to 150 kHz
  Beam Omni in xy plane

- F-33 (Acoustic Projector) - (Brighton Dam Facility)*
  Size - diameter 27.3 cm, length 5.2 cm

Beam -	frequency (kHz):	10	20	40		
	beam width (3 dB pts):	40°	20°	8°		
Power -	frequency (kHz):	10	20	30	40	50
	re 1 volt/μPa (at 1 meter):	128	142	147	152	154

For these measurements, the F-33 was driven much harder than 1 volt. The output Sound Pressure Level was approximately 180 dB.

D. Experiments

A summary of the basic experiments that were performed at Brighton Dam are given below.

1. CO_2 Laser Projector - Hydrophone Receiver: Bottom Reflectivity Measurements.
2. CO_2 Laser Projector - Hydrophone Receiver: Metal Plate Reflectivity Measurements.
3. CO_2 Laser Projector - Microphone Receiver: Water/Air Interface Measurements.
4. Acoustic Projector Microphone Receiver: Water/Air Interface Measurements.

A brief description of each experiment and the results obtained follows.

* Equipment Owner.

** Our measurements do not agree with this sensitivity figure.

1. CO_2 Laser Projector - Hydrophone Receiver: Bottom Reflectivity Measurements.

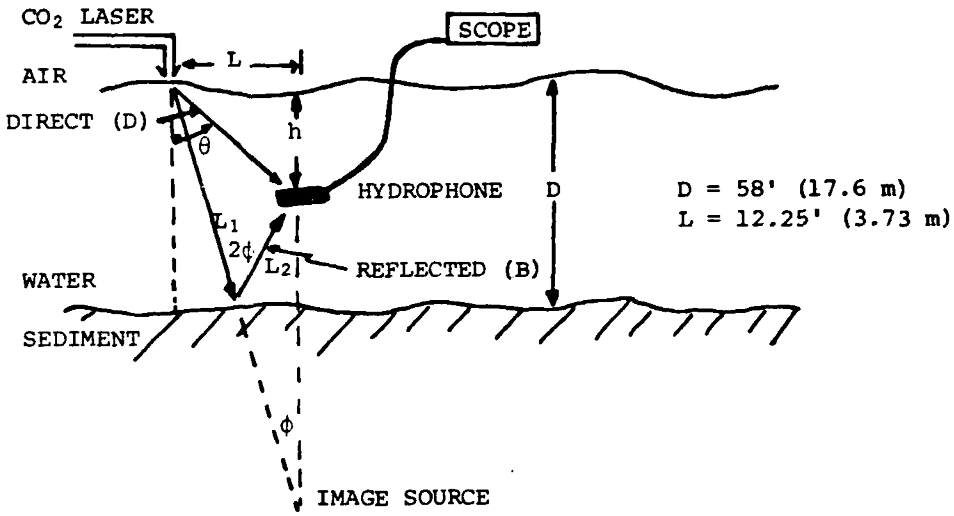


Figure 4 - Geometry Used in Experiments 1

a. Objective

The object of these measurements was to determine the acoustic source level and the reverberation level from the bottom produced by the CO_2 laser/acoustic source.

b. Measurements

Measurements of the Sound Pressure Level (SPL) produced by the CO_2 laser were made using the H-52 hydrophone located at water depths of h=10, 20, 30, 40 and 50 feet.

c. Results

Three distinct signals were observed in the scope pictures (Figure 5). The scope was triggered by the laser pulse, which occurs approximately 0.1 msec prior to the time that the laser beam hits the water. The initial pulse that occurs in the scope pictures is the signal that travels on a direct path from the point of laser impact on the water surface to the hydrophone (T_D). The second pulse to arrive at the hydrophone arrives after being reflected from the bottom sediment (T_B). The third pulse is the result of the acoustic energy that is initially reflected from the bottom sediment, the water surface, and back to the hydrophone (T_{BS}).

The set of scope photographs clearly shows these three distinct signals. Signals T_D and T_{BS} increase in time as the hydrophone is lowered into the water. While this is occurring with signals T_D and T_{BS}, T_B decreases in time and the spacing between T_{BS} and T_B increases. The calculated values of T_D, T_B and T_{BS}, given in each photograph, correspond closely to the times read from the scope traces. Other spurious signals shown on the traces have not been identified, although they probably arise from reflections resulting from the laboratory subsurface structure.

In later experiments instead of the hydrophone receiver being directly under the barge, it was used outside of the laboratory (still in the water). The scope traces showed considerably less noise than shown in Figure 5. Evidently there was considerable reverberation with the laboratory's subsurface structure causing an increase in the noise level.

Sound Pressure Levels (SPL's)

The output voltage from the hydrophone V_H after going through the system amplifier is given by

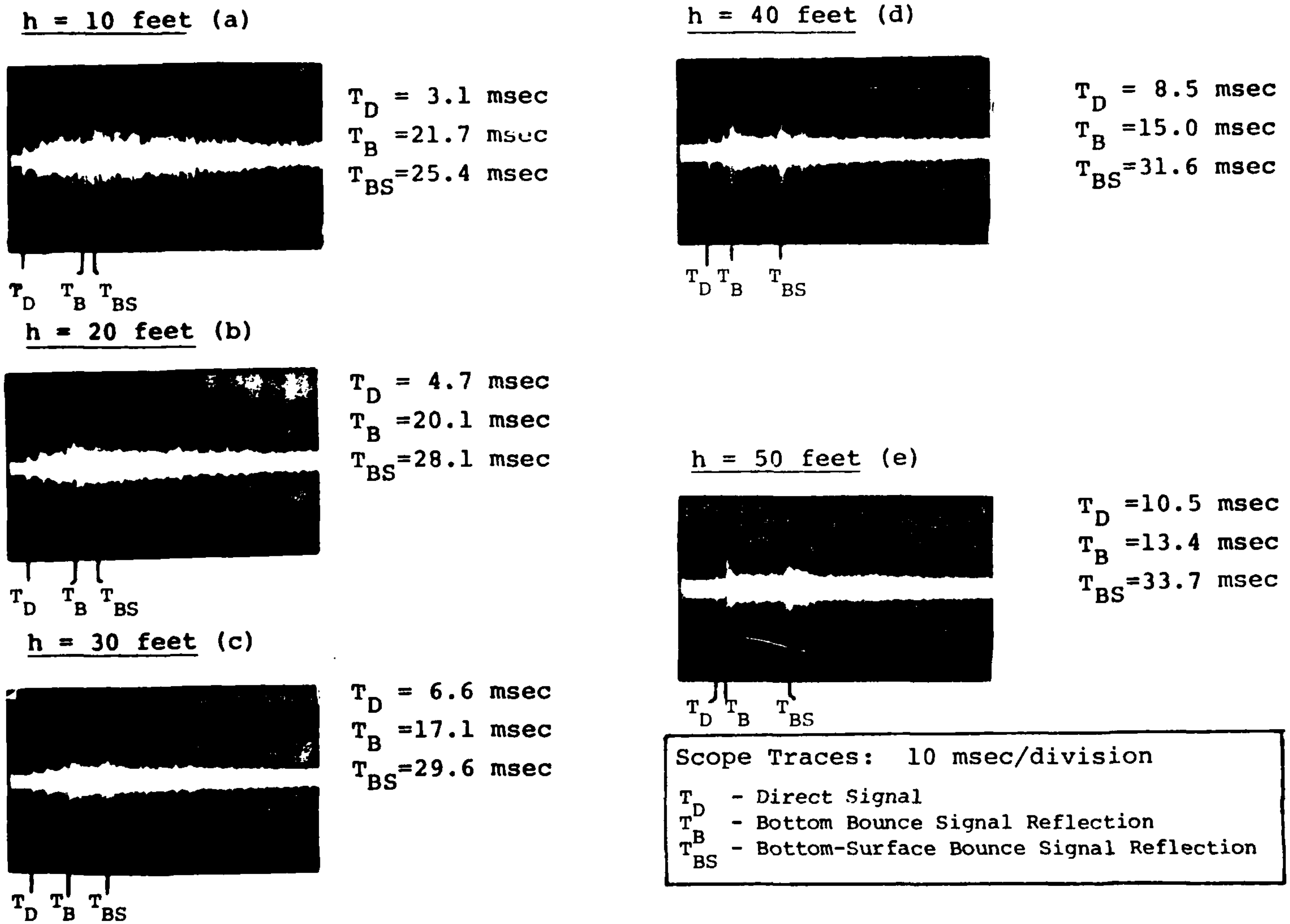


Figure 5 - CO_2 Laser Projector - Hydrophone Receiver: Reflectivity Measurements

$$V_H = P_H \times C_H \;\frac{G_v}{G_c} = \frac{\text{(peak-peak signal on scope)}}{\text{(peak-peak 1 volt cal. signal on scope)}} \quad (1)$$

where

P_H = pressure at the hydrophone

C_H = hydrophone sensitivity = -187 dB re 1 volt per μPa

G_v = amplifier gain for signal detection

G_c = amplifier gain for calibration = 1 (0 dB)

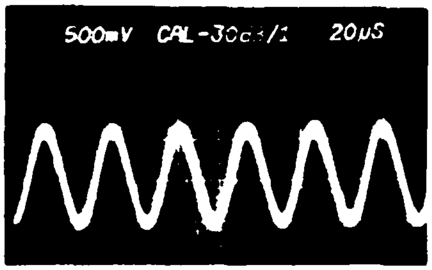
The Sound Pressure Level (SPL) is then calculated from

$$\begin{aligned} SPL &= \log P_H \\ &= 20 \log V_H - 20 \log G_v - 20 \log C_H \end{aligned} \quad (2)$$

$$SPL_{(\text{dB re } 1\ \mu\text{Pa})} = 20 \log V_H - 20 \log G_v + 187 \quad (3)$$

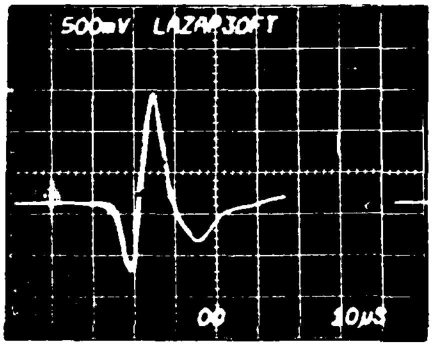
The scope traces given in Figure 5 clearly show the position of the pulses reflected from the various surfaces. However, at the time these measurements were made the amplifier gain of the system had not been calibrated. Figures 6B and 6C are traces similar to those of Figure 5, except that they can be calibrated using the data given in Figure 6A.

The scope trace of Figure 6A shows a peak-to-peak signal of 2.4 divisions for a 1 volt signal fed into the amplifier. Figure 6B shows a peak-to-peak signal of 4.3 divisions for the direct sound (D) detected by the hydrophone (delayed sweep). Figure 6C shows a complete pulse train of the various signals: direct (D), bottom reflection (B) and bottom surface reflection (BS). These amplitudes can be compared with the calibration signal (Figure 6A) to obtain values of the SPL's corresponding to each signal. Inserting the values for the calibration and direct signals into equation (3) enables one to calculate the SPL measured at angle θ by the H-52 hydrophone located in the position shown in Figure 4.



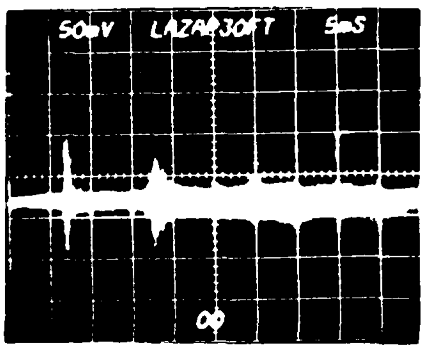
(A)

Calibration signal - 1 volt input to amplifier.



(B)

Signal detected at hydrophone due to direct pulse (T_D): from spot of laser impact to hydrophone (delayed sweep).



(C)

Pulse train at hydrophone showing direct and various reflected signals.

Figure 6 - Calibration of Hydrophone Signals

$$SPL_D(\theta) = 20 \log 4.3 - 20 \log 2.4 - (+30) + 187$$
$$SPL_D(\theta) = \underline{162\ dB}\ \text{re } 1\ \mu Pa$$

Equation (4) is used to convert the pressure $P(r,\theta)$ to the Intrinsic Sound Pressure ($P_o(r=1,\ \theta=0)$) one meter from the surface, directly under the impact position of the laser.

$$P(r,\theta) = \frac{P_o(r=1,\theta=0)\,\mathrm{Cos}\theta}{r} \tag{4}$$

or

$$P_o(r=1,\theta=0) = r\ P(r,\theta)/\cos\theta \tag{5}$$

and the Intrinsic Sound Pressure Level (at r=1 meter, θ=0) is given by

$$(SPL)_o = 20 \log P_o = 20 \log P(r,\theta) + 20 \log r - 20 \log \cos\theta \tag{6}$$

where

$$SPL_D = 20 \log P(r,\theta) = 162 \text{ dB re } 1\ \mu Pa$$
$$\theta = 22.2^\circ$$
$$r = 9.87 \text{ meters}$$

Inserting these values into equation (6) yields

$$(SPL)_o = 162 + 20.0 + 0.7 = \underline{182.7\ dB}\ \text{re } 1\ \mu Pa$$

The calculated SPL (20 log $P(r,\theta)$) at the hydrophone due to the bottom reflections assuming 100% specular reflection, can now be calculated using equation (6).

$$(SPL)_{(r,\theta)} = 20 \log P(r,\theta) = (SPL)_o - 20 \log r + 20 \log (\cos\theta)$$

where in this case

$$r = L_1+L_2 = 26.33\text{m (from the geometry of Figure 4)}$$
$$\theta = 8.14^\circ$$

Inserting these values into the equation for $(SPL)_{(r,\theta)}$ yields

$$(SPL)_{(r=26.33m,\ \theta=8.14^\circ)} = 182.7 - 28.4 - 0.09$$
$$= \underline{154\ dB}\ \text{re}\ 1\ \mu Pa$$

Similar calculations can be carried out to obtain the expected SPL's for the bottom-surface reflections. The results of these calculations along with the measured values for the SPL's of the various reflections are presented in Table 1. The difference between the measured and calculated SPL, i.e., 17.4 dB in the case of the bottom reflection, reflects the fact that there is a loss at the sediment instead of behaving like a 100% reflector. The difference (SPL_{calc} - SPL_{meas}) for the bottom-surface reflection (BS) is given as 20.2 dB. Subtracting 17.4 dB for the bottom reflection (B) yields a reflection loss of 2.8 dB at water surface. The true reflection loss at the water surface is probably less than 1 dB.

SIGNAL	SCOPE DEFLECTION (PK TO PK)	REFLEC: (X) / DIRECT: (D)	L 20 log X/D (dB)	$SPL_{meas.}$ (162+L) (dB)	$SPL_{calc.}$ (dB)	$SPL_{calc.}$-$SPL_{meas.}$ (dB)
BOTTOM REFLECTION (B)	2.3/10	0.23/4.3	-25.4	136.6	154	17.4
BOTTOM - SURFACE REFLECTION (BS)	1.0/10	0.1/4.3	-32.7	129.3	149.5	20.2

Table 1 - Measured SPL's for Reflected Acoustic Signals

2. CO_2 Laser Projector - Hydrophone Receiver: Metal Plate Reflectivity Measurements

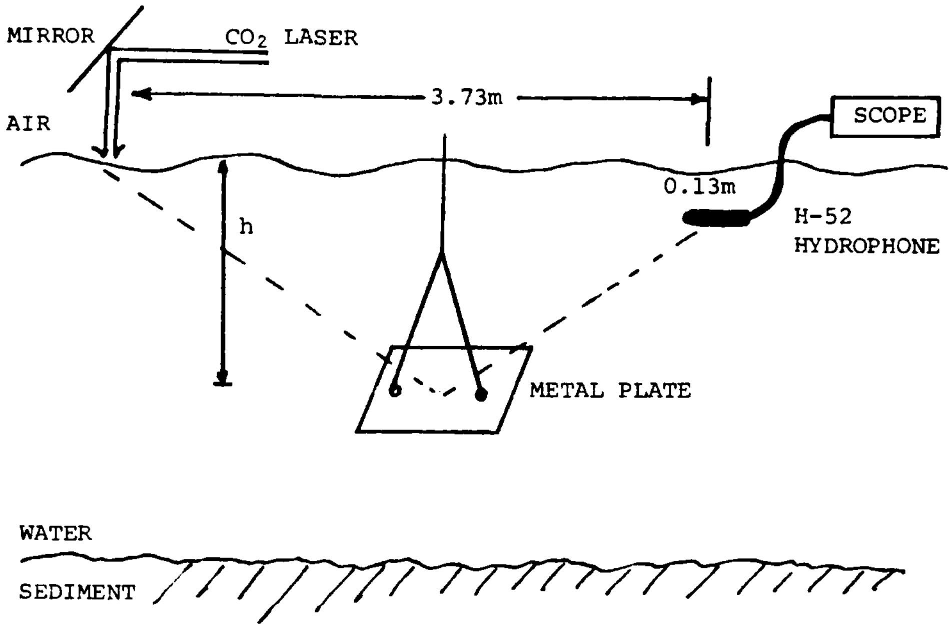


Figure 7 - Geometry Used in Metal Plate Experiment

a. Objective

The object of these measurements was to determine the feasibility of using an airborne CO_2 laser system for detection of objects near or on the sediment floor.

b. Measurements

The experiments were designed to measure the acoustic signal from a metal plate (≈ 2 ft^2) as it was lowered into the water. Sound Pressure Levels were made with the hydrophone located 0.13 m below the water surface for various depths of the metal plate: h=55, 50, 45, 40, 30 and 20 feet.

c. Results

The scope pictures (Figure 8) show the metal plate reflection as a function of plate depth in the water. The position (in time) of the reflection from the metal plate (T_M) moved systematically from a value of 23 msec, for the case where the plate is located in 55 feet of water to a value of 8 msec for a plate depth of 20 feet. In all cases the bottom reflection remained constant at 24 msec. The bottom reflection structure also remained fairly constant when the plate was removed.

Figure 8A shows that the signal from a small metal plate located close to the bottom (≃2.4 feet) can be detected in the presence of a large bottom sediment reflection. It should be noted that these measurements were made for the case where the CO_2 laser was used as the source of acoustic energy. The peak of this energy spectrum was approximately 25 kHz which may or may not be the optimum acoustic energy for this application.

Sound Pressure Levels

Assuming 100% specular reflection for the metal plate as assumed for experiments (1), the Sound Pressure Level's (SPL's) can be calculated by equation (7), i.e.,

$$SPL = 185 + 20 \log \cos\theta - 20 \log R_T \qquad (7)$$

where R_T is the total path length of the acoustic signal, i.e., from origin to the metal plate and back to the hydrophone.

The results of these calculations for various plate depths are presented in Table 2. Also included in this table are the actual SPL's measured by the hydrophone. The difference between $SPL_{calc.}$ and $SPL_{meas.}$ is attributed to the loss at the aluminum plate.

The average loss at the aluminum plate is calculated as 20.6 dB, which appears to be an extremely large loss. Based on the ρc values (ρ=density, c=velocity of sound) for aluminum

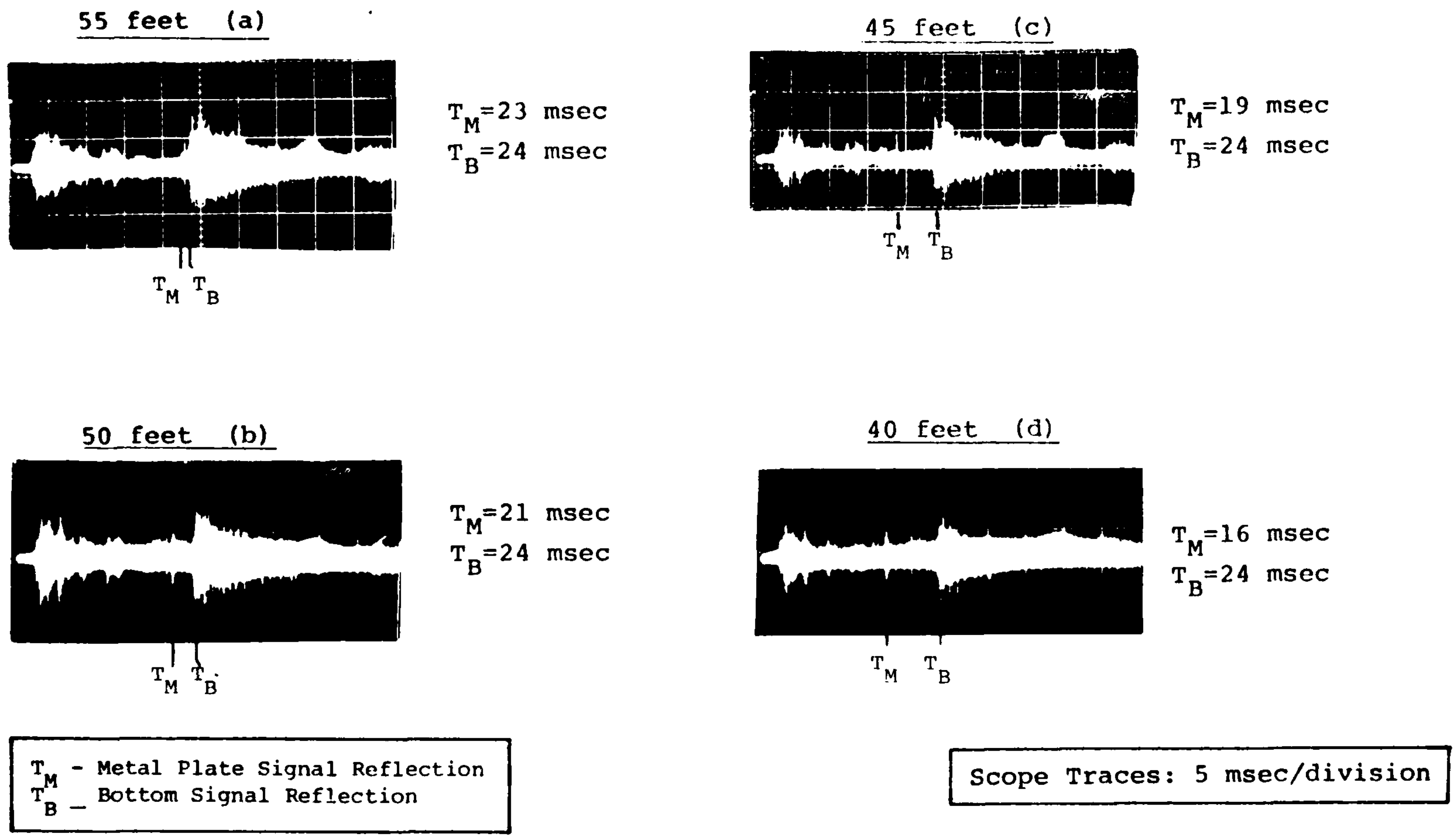
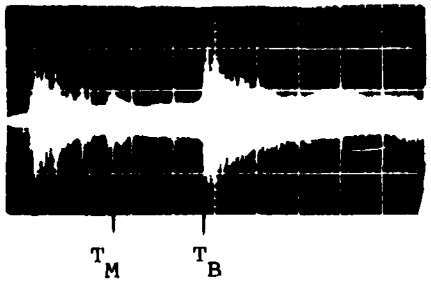


Figure 8 - CO_2 Laser Projector - Hydrophone Receiver:
Metal Plate Reflectivity Measurements

30 feet (e)



T_M=12 msec
T_B=24 msec

20 feet (f)

T_M= 8 msec
T_B=24 msec

No Plate (g)

T_M - Metal Plate Signal Reflection
T_B - Bottom Signal Reflection

Scope Traces: 5 msec/division

Figure 8 - CO_2 Laser Projector - Hydrophone Receiver
Metal Plate Reflectivity Measurements
(Continued)

and water, this loss is calculated to be 3.2 dB. This large discrepancy between measured and calculated loss at the aluminum plate is thought to be due mainly to misalignment of the hydrophone receiver with respect to the aluminum plate. Large variations in received voltage signals were observed on the scope as the plate was lowered into the water. These variations show that the reflectivity is highly specular and that the signal is sensitive to the alignment of the plate with respect to the hydrophone receiver.

D (ft/meters)	L_1+L_2 (Meters)	20 log cosθ (dB)	20 log (L_1+L_2) (dB)	SPL_{calc} (dB)	SPL_{meas} (dB)	Loss (dB)
20/6.1	12.6	-0.4	-22.0	162.6	143.2	19.4
30/9.1	18.5	-0.2	-25.3	159.5	141.3	17.7
40/12.2	24.6	-0.1	-27.8	157.1	131.8	25.3
45/13.7	27.5	-0.1	-28.8	156.1	131.8	24.7
50/15.2	30.5	-0.1	-29.7	155.2	136.2	19.0
55/16.8	33.7	-0.1	-30.5	154.4	136.2	18.2
					Avg.	20.6

Table 2 - Comparison of Calculated and Measured SPL's for Acoustic Signals Reflected from a Metal Plate.

3. CO_2 Laser Projector - Microphone Receiver: Water/Air Interface Measurements

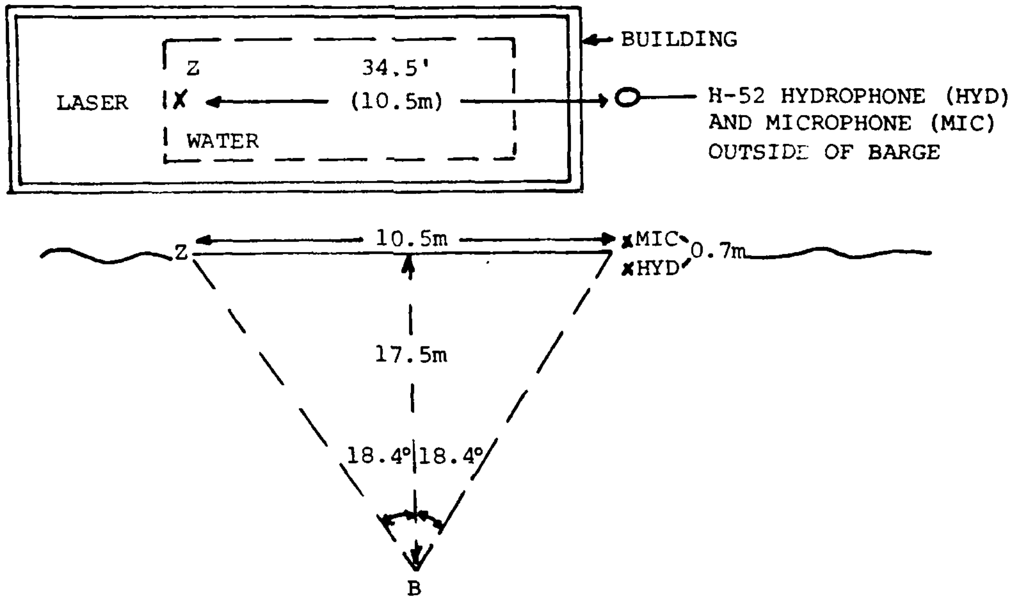


Figure 9 - Geometry Used in Laser/Microphone Experiments

a. Object

The object of these measurements was to determine the feasibility of detecting Sound Pressure Levels (SPL) (generated in the water) by a microphone receiver located in the air.

b. Measurements

The CO_2 laser was used to set-up the acoustic field in the water at point Z while an ultra sensitive microphone, flat to 40 kHz, was positioned approximately 1 foot above the water surface and used to detect the acoustic energy transmitted through the water/air interface. The microphone was also shielded from spurious acoustic sources. The H-52 hydrophone detected the SPL in the water, just under the water surface, before the sound passed through the water/air interface. In the initial tests, both hydrophone and microphone were located inside the laboratory building. This was shown to be ineffective because of the noise generated by both the pulsing of the CO_2 laser and the thermal blow-off at the water surface. The majority of this noise disappeared by taking the receivers out of the laboratory building.

c. Results

The scope pictures showing the responses of the hydrophone and microphone are shown in Figure 10. Figure 10(a) shows the hydrophone's response with the bottom reflected signal (T_{HYD}) occurring at 23.9 msec. Figure 10(b) shows the equivalent microphone's response (T_{MIC}) to occur at 25.4 msec., or 1.6 msec. after that of the hydrophone. This time difference is due to the 28 inches that separates the two receivers.

The calculated times of arrival of the bottom signals at the hydrophone and microphone correspond almost exactly with the values read from the scope traces. In addition, Figure 10(c) shows that the signal disappears in the case where the microphone was shielded from the acoustic signal. It has been definately proven that the signal detected by the microphone is actually the acoustic signal reflected from the bottom. This acoustic signal has traveled 2 x 58 feet in water, reflected off the bottom sediment and penetrated the water/air interface.

Sound Pressure Levels

The hydrophone H-52 amplifier gain was adjusted, see Figure 10(d), to yield a peak-to-peak value on the scope of 2 divisions when a 50 dB gain was added to the system. Using the H-52 sensitivity of -187 dB re 1V μPa, the calibration factor is

$$\text{Cal. Fac.} = -50 - (+187) = +137 \text{ dB re } 1\ \mu\text{Pa}$$

Figure 11(a) shows the strength of the reflected signal as a peak-to-peak signal of 3 divisions or a signal that is 20 log

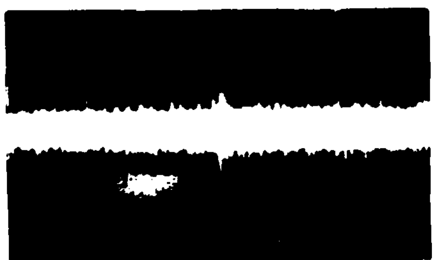
Hydrophone - H52 (a)

T_{HYD}

T_M=23.9 msec

Microphone - (Shielded) (c)

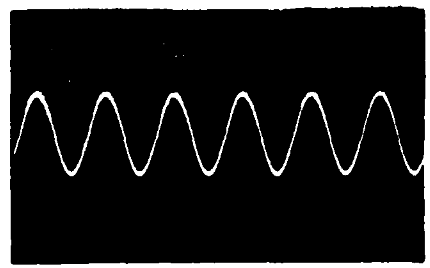
Microphone (b)



T_{MK}

T_M=25.4 msec

Calibration Signal



Scope Traces: 5 msec/division

Figure 10 - CO_2 Laser Projector - Microphone Receiver:
Water/Air Interface Measurements

3/2 = 3.5 dB larger than the calibrated signal. The SPL at the hydrophone is therefore given by +137 + 3.5 or = +140 dB re μPa. Assuming a 30 dB loss of the acoustic signal in passing through the water/air interface results in an expected SPL at the microphone in air of 140.5 -30 = 110.5 dB re 1 μPa.

An attempt was made to compare the predicted SPL at the microphone with the value detected according to the microphone sensitivity calibration. Large discrepancies (≈30 dB) occurred between the predicted and measured SPL's at the microphone. We experienced extreme problems with the microphone's preamplifier and possibly was the main cause of the large discrepancies. Other factors that could have contributed to our problems were: a) large algal concentration in the surface waters and b) radiation pattern of the microphone.

4. Acoustic Projector - Microphone Receiver: Bottom Reflectivity Measurements

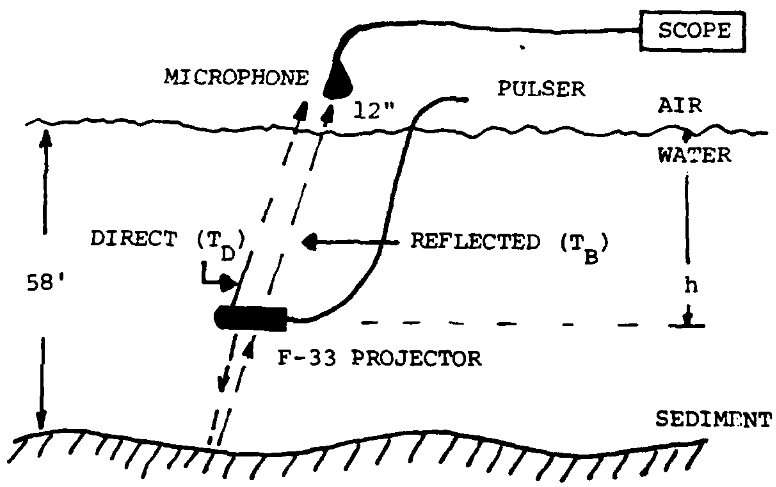


Figure 11 - Geometry Used in Experiments 4

a. Objective

The object of this set of measurements was to obtain Sound Pressure Levels (SPL) at a microphone located in the air from acoustic signals created in the water.

b. Measurements

The F-33 acoustic projector at Brighton Dam was used in these tests to generate the acoustic energy. This projector is extremely versatile as it can be pulsed and swept in frequency to 150 kHz. SPL's were measured at the microphone for three different water depths (h): h=20, 30 and 40 feet and three different frequencies: f=20, 22 and 24 kHz.

c. Results

The results of these tests are shown in Figure 11. The first signal (T_D) to arrive at the microphone is the signal that comes directly from the hydrophone. The second signal (T_B) originates from the acoustic energy that is reflected from the sediment back to the microphone. The timing of T_D increases and T_B decreases as the projector is lowered into the water. This is in agreement with what one would expect. The calculated time of arrival of the signals are in fair agreement with the values read from the scope traces. In one case there is approximately a 1 msec. unexplained difference. There also appears to be something peculiar occurring with the signals as the projector is lowered from 30 to 40 feet. The intensity of T_B should increase as the projector is lowered, however, T_B is lower in intensity at 40 feet and in Figure 11(c) T_B is not observed. This may be due to self shielding effects of the hydrophone on the microphone. Also of interest are the additional signals which occur at 22 kHz between 13-17 msec. These signals may be due to various absorption resonance phenomena that occur with matter in the water.

SPL calculations for the microphone in air again proved to yield results which were approximately 30 dB

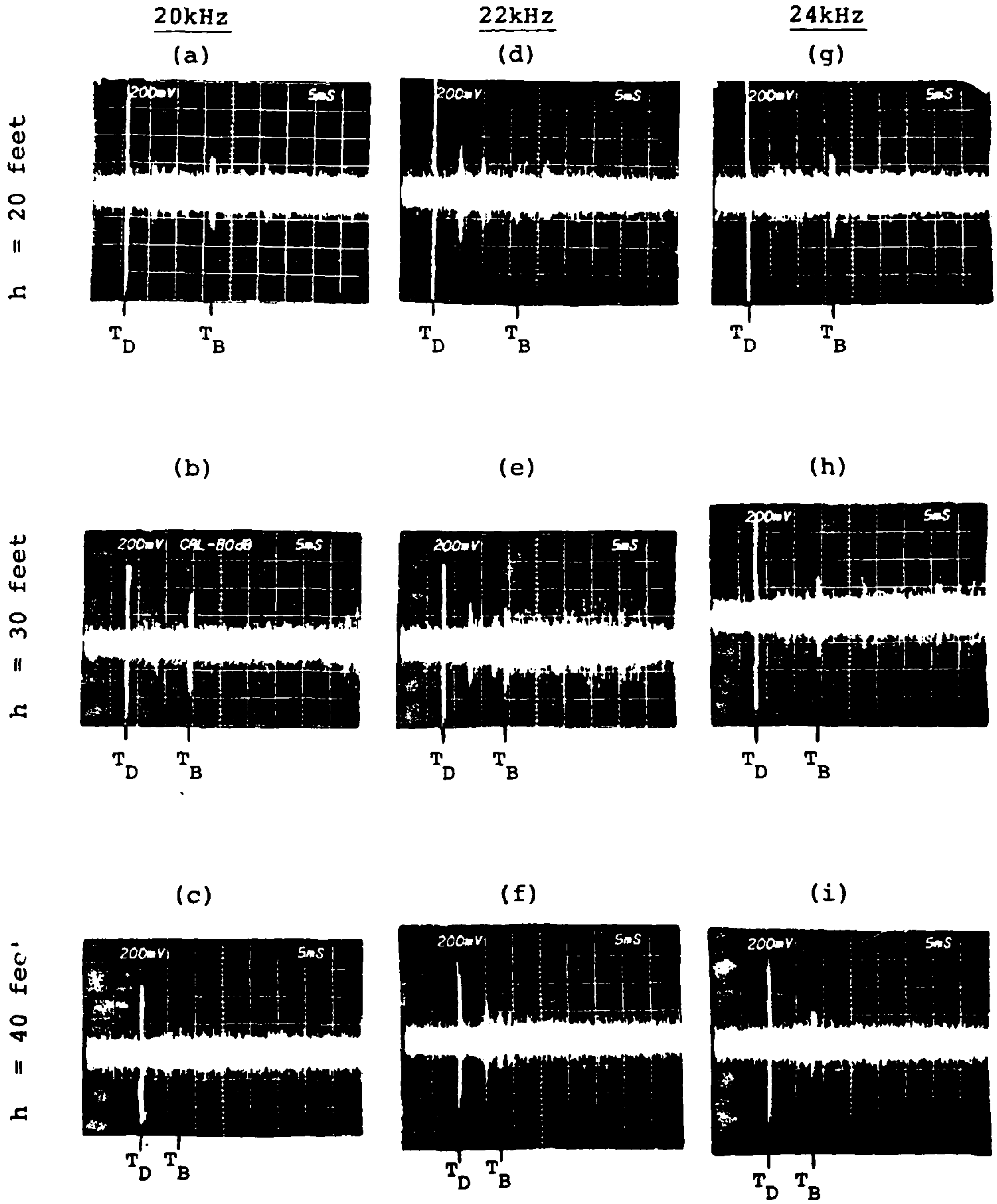


Figure 11 - Acoustic Projector - Microphone Receiver: Sediment Reflectivity Measurements

too low. Therefore, either the stated microphone sensitivity is too low or the signal experienced an unexplained additional 30 dB loss.

A second set of experiments, similar to the above experiments were performed. In these measurements the hydrophone projector (F-41) was located at depths of 30', 40' and 50' (acoustic energy projected upwards). The H-52 hydrophone was located at a depth of 10' below the water surface, while the microphone was located directly over the H-52 at a distance of 1' in the air. Figure 12 gives the response of the H-52 receiver for two depths of the F-41 projector. Figure 13 is the response curve for the microphone receiver for various positions for the F-41 projector. The following values for the response figures for the hydrophone and microphone, at 25 kHz, were obtained from these figures.

Hydrophone (H-52): -43 dB re 1 Volt
Microphone : -83 dB re 1 Volt

Using the sensitivity for the H-52 as 187 dB re 1 Volt/μPa the SPL is calculated as

$$SPL = -43 + 187 = 144 \text{ dB re } 1\ \mu\text{Pa (at 10')}$$

Converting this SPL to a value at the water surface and assuming a 30 dB loss at the air/water interface yields the following value for the SPL at the microphone.

$$SPL_{MIC} = 144 - 20 \log \frac{30'}{20'} - 30$$

$$= 144 - 3 - 30 = \underline{111 \text{ dB}} \text{ re } 1\ \mu\text{Pa}$$

The measured microphone sensitivity of -83 dB re 1 volt is used in the following expression to calculate the sensitivity (S) of the microphone.

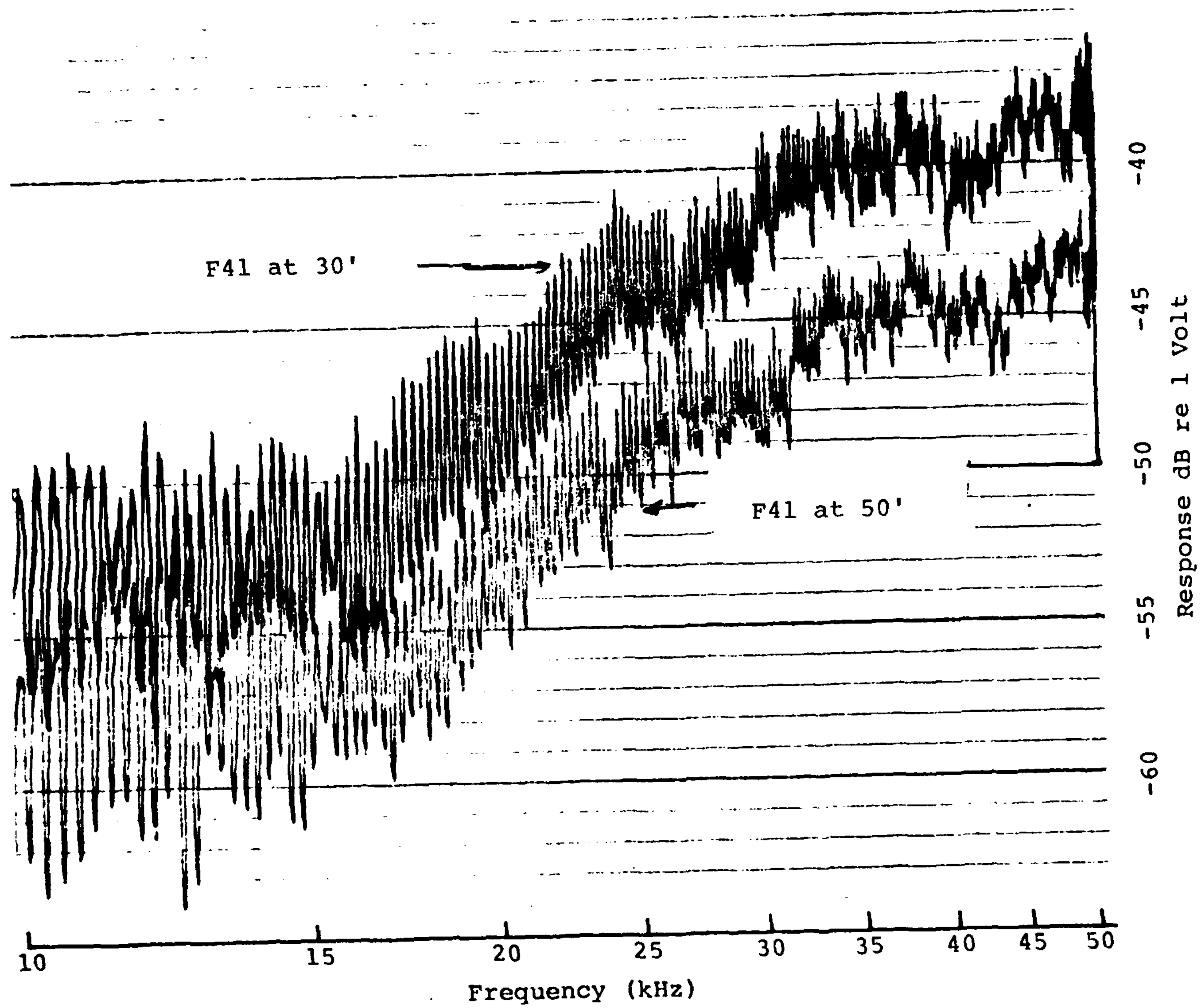


Figure 12 - HYDROPHONE H-52 RESPONSE

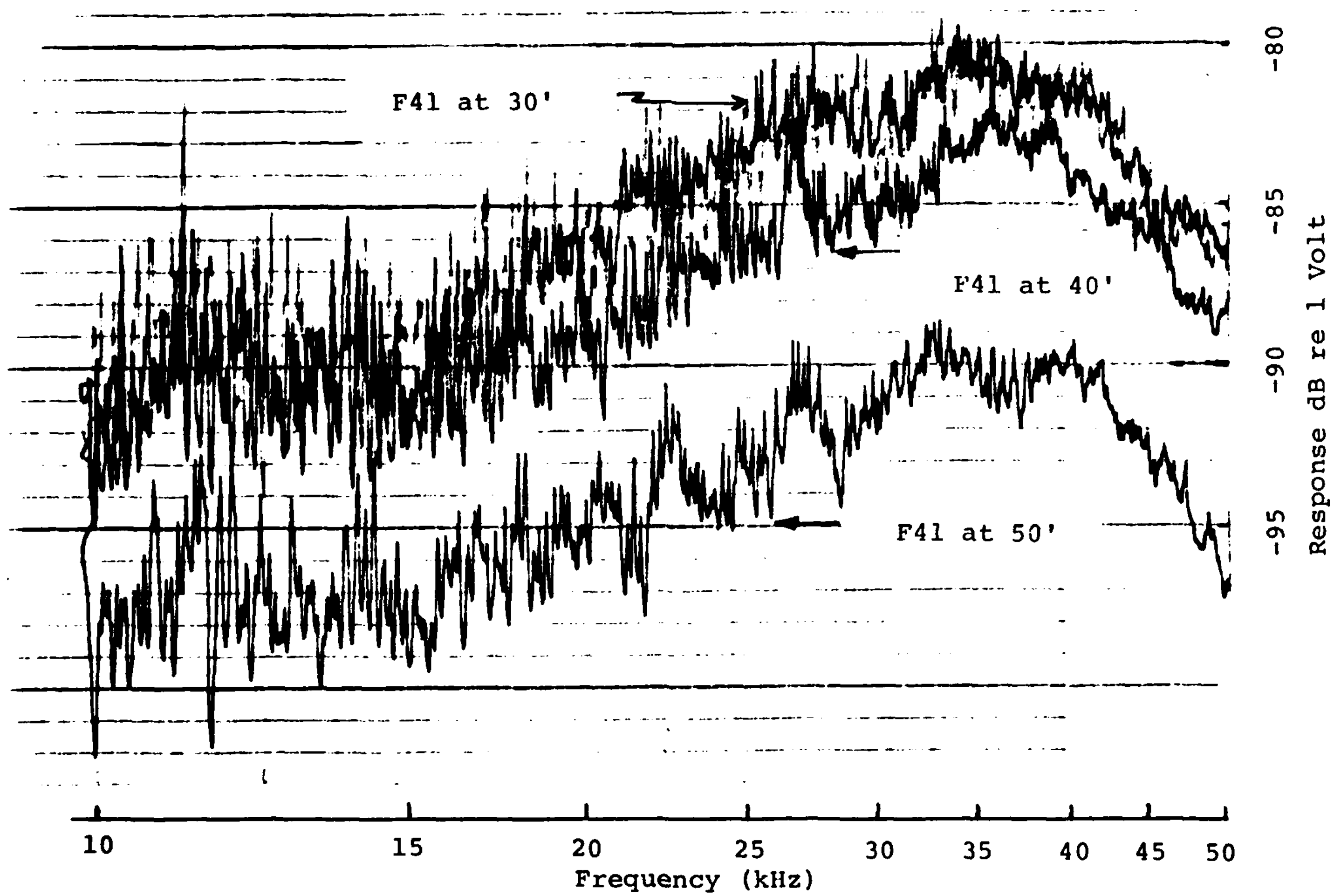


Figure 13 - MICROPHONE RESPONSE

$$-83 \text{ dB re 1 volt} - (S) = 111 \text{ dB re 1 } \mu\text{Pa}$$

and

$$S = -194 \text{ dB re 1 Volt}/\mu\text{Pa}$$
$$= -74 \text{ dB re 1 Volt/Pa}$$

The sensitivity specs for the microphone is given as -38 dB re 1 volt/Pa or approximately 36 dB higher than the sensitivity found in this set of measurements.

The only conclusion that can be arrived is that a) the microphone specs are incorrect or b) there is a 30 dB loss in the measurements that has not been explained.

D. Summary

The results of the various experiments of Phase II have been presented in the scope traces shown in Figures 5, 8, 10 and 11 of Section II.C. These results showed that an acoustic signal generated either in the water or at the water surface could, after penetrating 58 feet - reflected from the bottom sediment - backscattered through 58 feet, be detected at a microphone located in the air. Some of these results also appeared to be a function of frequency, thereby indicating that it might be possible to use ratio techniques of different acoustic frequencies to derive information about the type of matter in the water or the type of bottom sediment. In addition, the possibility exists that the CO_2 laser/acoustic technique could be used to remotely detect and localize objects either on or near the bottom.

The time of arrival of the various reflected acoustic signals have been shown to correspond closely to the calculated times. Calculations of the Sound Pressure Levels (SPL) of the various reflection surface have been made. In general, the SPL's in the water agree with predictions. However, large discrepancies exist between the predicted and measured values of the SPL's in air. These discrepancies have not been resolved, but will be one of the prime objectives for future experiments.

APPENDIX A

CO_2 Laser Induced Acoustic Pulses

It has been shown that the interaction of pulsed infrared laser radiation with a free water surface produces acoustic pulses - this is called "surface blowoff". In this case, the major portion of the incident energy is absorbed at the water surface causing boiling and subsequent expansion of water vapor. The sound pulse in the water is the reaction to the blowoff of the surface material.

The theory of explosive laser beam-water interaction is mainly qualitative at the present time. A crude analysis using conservation of momentum and energy shows that the pressure pulse produced in the water results from the vaporization of material from the surface of the water. This analysis shows that the average pressure exerted over an area, A, is given by:

$$P = \frac{1}{A} \cdot \frac{dp}{dt} = \frac{V_m}{H} \cdot I$$

where

p = Momentum
V_m = Mean velocity of explosive evaporation
H = Energy in heating the unvaporized fluid
I = Intensity of laser beam

This equation shows that the pressure is directly proportional to the intensity of the radiation. At very high intensities, experiments have shown the pressure to increase at a slower rate than is given by this simplified model.

With laser beam intensities used in previous experiments, evaporation of the material is so rapid that the surface from which the evaporation is taking place moves into the fluid at supersonic velocities. Thus, this interaction creates a shock wave that propagates into the water. Studies performed with laser pulses lasting 0.1 msec. have shown that the shock velocity drops to sound velocities in approximately 0.5 msec. after pulse termination. The sound pulse then continues into the medium with a pressure that is less than the initial shock pressure. Acoustic signals in the ocean produced with the CO_2 laser have been detected at distances in excess of 3000 feet.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AST-R-070580	2. GOVT ACCESSION NO. AD-A094 694	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Feasibility Study of Airborne Bathymetric Sensing Using the CO_2 Laser/Acoustic Technique: (Brighton Dam Test Results)		5. TYPE OF REPORT & PERIOD COVERED Interim: September 1978 - November 1979 6. PERFORMING ORG. REPORT NUMBER -----
7. AUTHOR(s) G. D. Hickman B. S. Maccabee C. E. Bell		8. CONTRACT OR GRANT NUMBER(s) N00014-78-C-0764
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Science Technology, Inc. 1011 Arlington Blvd, Suite 317 Arlington, Virginia 22209		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Code 462 800 North Quincy Street Arlington, Virginia 22217		12. REPORT DATE May 1980 13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE ----

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

CO_2 Laser
Remote Sensing
Acoustic Bathymetry
Aircraft Sensors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Reverse

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A feasibility experiment was performed on a concept for a remote turbid water bathymetric system for shallow water mapping. The concept consists of a CO_2 laser transmitter and a microphone receiver. The CO_2 laser is used from a platform in the air to generate an acoustic field in the water, while the microphone (in air) detects the sound pulses, after being reflected off the bottom sediment. The results of these experiments definitively proved that the CO_2 laser/acoustic technique could be used to derive bathymetric data using a microphone located in the air. The possibility therefore exists that this technique could be used as the basis for a remote sensing system for shallow water bathymetry. Similar type measurements were also made of acoustic reflections from an aluminum plate at various water depths. Calculations of the Sound Pressure Levels (SPL) are in good agreement with SPL's measured with a hydropphone in the water. However, large discrepancies exist between measured and calculated SPL's with the air-located microphone. The resolution of these discrepancies, which are thought to be due to a malfunction of the microphone, will be the objective of future experiments.

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